Radiation Efficiency Analysis of Balanced-Impedance Hexaferrite Substrate for Antenna Miniaturisation

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Abstract

Antenna miniaturisation in the low UHF band is required since the wavelengths are large compared to portable consumer terminals. Magneto-dielectric substrates such as hexaferrites which increase μ_r as well as ε_r have received attention for their miniaturisation potential, however there is a shortage of published results for the radiation efficiency of such antennas based on full 3D radiative characterisation in free space conditions. In this work, patch antennas fabricated on hexaferrite, FR-4 and RT5880 substrates were examined through simulation, fabrication and radiative measurement. While the frequency in hexaferrite was reduced by a factor of six compared to the RT5880 antennas, the efficiency in the hexaferrite antennas was low. The combined effect of the losses in the hexaferrite and the electrically small size of the resulting patch antenna limits its use in long range transmitting applications, though it may still find application in short range or receiver applications.

1 Introduction

There is an ongoing need for antenna developments in the low UHF band below 1000 MHz. Vacation of the analogue TV broadcast bands offers the opportunity to deploy "whitespace" devices in the band 470–790 MHz [1, 2]. Similarly, control-plane communications for 5G and increasing volume of machine-to-machine communication can utilise the long-range, low-data rate channels associated with the low UHF band. Alternatively, short range UHF applications exist in the context of RFID readers and wireless medical devices [3]. In any of these cases the wavelengths involved necessitate antenna miniaturisation in consumer devices.

Many examples exist of patch antenna miniaturisation with a substrate of dielectric permittivity ε_r. While the patch antenna offers favourable broadbeam radiation pattern characteristics and reasonable efficiency provided the dielectric losses are low [4], the miniaturisation offered by the wavelength compression potentially requires very high dielectric permittivity values ε_r to compress the large wavelengths into an acceptable volume. The patch antenna is known to be intrinsically relatively narrowband compared to the half-wavelength wire dipole for example [4], with the bandwidth still further reduced by increased ε_r [5].

Magneto-dielectric substrate materials have been proposed to counter the bandwidth problems associated with patch antenna miniaturisation [5]. Increasing both magnetic permeability μ_r and ε_r greatly increases the resultant antenna miniaturisation, reducing the bandwidth reduction associated with high values of increasing ε_r [5]. While magneto-dielectric loading elements have been tested in various forms to provide varying degrees of antenna miniaturisation [3, 6, 7, 8, 9, 10, 11, 12], there is a shortage of works recording the full 3D radiative characterisation of these antennas using these substrates.

In this work a balanced-impedance hexaferrite (HXF) material, as well as samples of FR-4 and Rogers RT5880, were characterised using a Keysight E4991B impedance analyser. The 3D radiation patterns and efficiency characteristics of patch antennas built on these substrates were then analysed in simulation (CST Microwave Studio) and free space radiative measurement.

2 Background

2.1 Balanced wave impedance and hexaferrites

A theoretical lossless magneto-dielectric substrate for patch antennas was examined in [5]. That work inspired many others by noting that patch antenna bandwidth would be degraded more slowly with increasing miniaturisation factor $n = \sqrt{\mu_\mathrm{r} \times \varepsilon_\mathrm{r}}$, if increased μ_r was used to provide some of the increase in refractive index n as opposed to increasing ε_r in isolation. In addition to achieving high n, various authors have attempted to satisfy the "balanced wave impedance" criterion during material design [7, 13], wherein satisfying $\mu_\mathrm{r} = \varepsilon_\mathrm{r}$ causes the material to exhibit the same wave impedance as free space [13], giving the patch similar bandwidth to the same-sized patch with no substrate [5]. The wave impedance Z is given by:

$$Z = \sqrt{\frac{\mu_\mathrm{r}}{\varepsilon_\mathrm{r}}} \times 377\ \Omega \tag{1}$$

For antenna applications at UHF frequencies, hexaferrites are comparatively unique in offering control over μ_r and ε_r at frequencies not coincident with extremely lossy ferromagnetic resonances associated with common spinel and Ni-Zn ferrites [6]. Observation of the recent literature indicates that while

μ_r and ε_r can be controlled, minimum loss tangent may not coincide with the desired μ_r and ε_r values at a target frequency [7, 13]. Thus, the bandwidth advantage conferred by impedance matching the substrate to the channel may be nullified by high loss tangent, resulting in low efficiency.

2.2 Review of hexaferrite antennas

Various miniaturised antennas have been reported with hexaferrite elements, including wire-wound conductors on hexaferrite chips [8, 9] and patches with substrates that were solid tiles [10, 11], flexible [3] or a lattice of hexaferrite bars [12]. While all of these works observed miniaturisation, varying approaches to performance analysis especially with regard to the treatment of loss tangent and efficiency lead to differing conclusions on the applicability of the antenna to various communication problems.

Where high radiation efficiencies have been reported, these appear to be limited to designs which use hexaferrite chip loading elements such as [8, 9, 12], where the miniaturisation is less pronounced than that observed in conventional patch designs due to the lower filling factor. Conventional patch designs achieve greater miniaturisation [10, 11, 3] but the utility of these designs for common communication problems depends on whether loss tangent and efficiency has been given full consideration. The works of [10, 11] overlook loss tangent, wherein LTE MIMO is proposed as a possible application. Without an analysis of loss tangent, this view may be compromised by low radiation efficiency.

In contrast, works presenting detailed analysis of the loss tangents in hexaferrite patches such as [3] advance the view that hexaferrite patches are mostly applicable to short range communications such as RFID or health monitoring. The low gain of even relatively low-loss hexaferrites makes hexaferrite miniaturisation best suited to cases where miniaturisation is of paramount importance compared to concerns of efficiency.

3 Antenna design

3.1 Material characterisation

The hexaferrite was a composite of 75% Co_2Z-phase to 25% Co_2Y-phase ferrite [13], chosen for its near-balanced ε_r and μ_r at UHF frequencies. Additionally, that work gave sufficient detail of the fabrication procedure to allow an external supplier to attempt to reproduce the material characteristics (Trans-Tech Inc., USA). The impedance characteristics of the hexaferrite material were measured using a Keysight E4991B impedance analyser over the frequency range 1–1000 MHz (Figure 1), along with those of FR-4 and Rogers RT5880 (plots omitted for brevity). The wave impedance Z (Eqn. 1) of each sample is given in Figure 2.

While the balanced-impedance criterion $Z = Z_0$ was only satisfied in the hexaferrite sample at a single frequency of 944 MHz, it can be seen by inspection that the Co_2Z hexaferrite was better

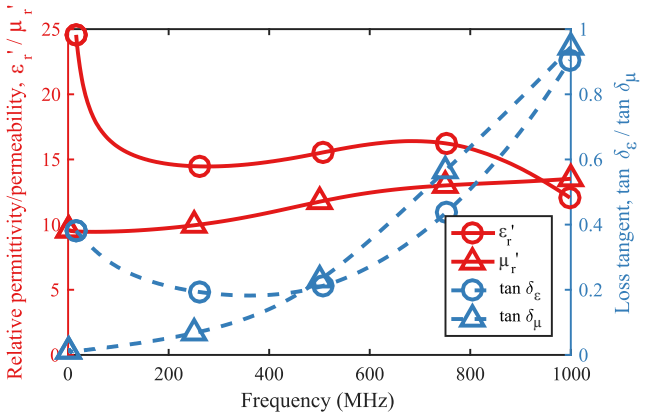


Fig. 1: Relative real permittivity, real permeability and loss tangent characteristics of hexaferrite sample.

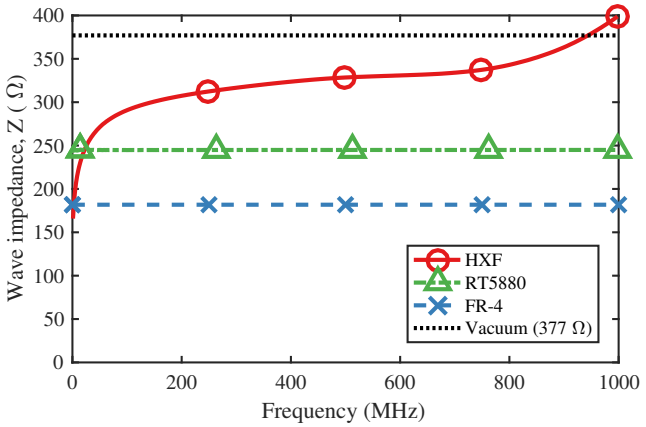


Fig. 2: Substrate wave impedance Z (Eqn. 1).

matched to the medium than the dielectric substrate samples. However, the loss tangents in the hexaferrite material were considerably higher than those measured for the dielectric materials, and also higher than those reported for the reference hexaferrite (Z75) as compared in Table 1. Ceramic UHF properties are recognised to be dependent on the material processing history [13], hence some variation from the reference characteristics was expected.

Material	Frequency (MHz)	ε_r	μ_r	$\tan\delta_\varepsilon$	$\tan\delta_\mu$
HXF	329	14.5	10.4	0.18	0.10
HXF	450	15.1	11.3	0.19	0.18
HXF	650	16.3	12.7	0.32	0.42
"Z75" [13]	650	13.5	12.3	0.04	0.25
FR-4	1–1000	4.4	-	0.015	-
RT5880	1–1000	2.3	-	0.0003	-

Table 1: Selected substrate UHF characteristics.

3.2 Antenna layout selection

A set of hexaferrite patch antennas were designed and simulated with the layouts given in Figure 3. The patch widths (50.0, 35.0 mm) were selected to target two frequencies: the lowest frequency available (subsequently measured to be 329 MHz), and 433 MHz (ISM band). The patch lengths (33.0, 15.0 mm) and feed track positions were selected to provide impedance matching to a 50 Ω coaxial line. The hexaferrite tiles were limited to maximum dimensions of 50 mm × 50 mm × 2 mm by the manufacturing process. The dimensions were maintained for antennas fabricated on FR-4 and RT5880 substrate to permit a study of antenna miniaturisation based predominantly on the change in substrate, except for varying the feed position to obtain a suitable feed match.

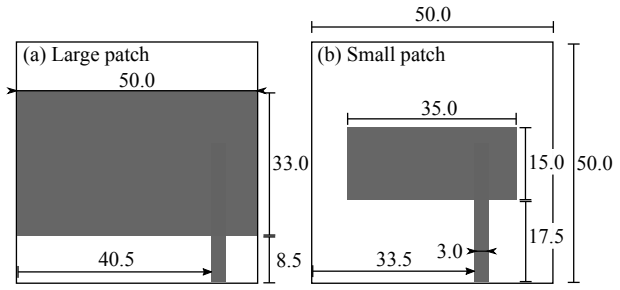
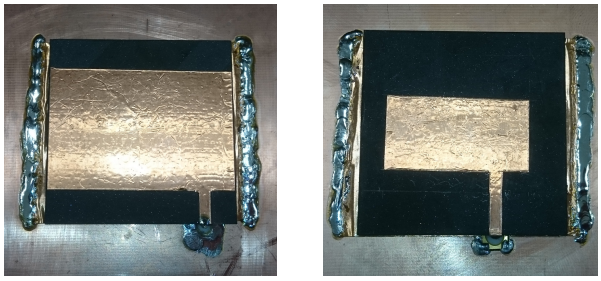


Fig. 3: Hexaferrite patch antenna layout. Dimensions in mm.



(a) Large patch (329 MHz) (b) Small patch (450 MHz)

Fig. 4: Fabricated hexaferrite patch antennas.

4 Antenna Measurements

4.1 Input response

The simulated and measured input responses (S_{11}) are shown in Figure 5, demonstrating the frequency reduction caused by the increased refractive index of the hexaferrite material. The frequency reduction factor is given relative to the measured frequency of the RT5880 antenna in each case by $\frac{f(\text{RT5880})}{f(\text{meas})}$ in Table 2. The electrical smallness factor $ka = 2\pi a/\lambda_0$ is calculated, where $a = 35.4$ mm is the radius of the smallest sphere inscribing the antenna and feed track within its limits. Antennas with ka factors smaller than 0.5 may be classed as electrically small and are susceptible to exhibiting low radiation resistance r_{rad}, which may subsequently lead to low radiation efficiency even for modest substrate loss factors [4].

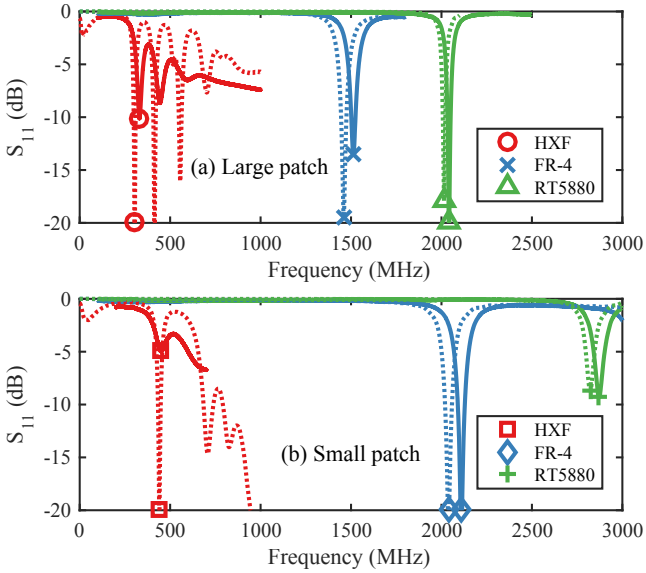


Fig. 5: Input response S_{11} of patch antennas. Solid lines denote measured results, dashed lines denote simulated results.

Antenna	Freq. (MHz)	Frequency reduction factor	ka
HXF large	329	6.2	0.24
FR-4 large	1514	1.3	1.12
RT5880 large	2042	(1)	1.51
HXF small	450	6.4	0.33
FR-4 large	2110	1.4	1.56
RT5880 large	2872	(1)	2.14

Table 2: Frequency reduction and electrical smallness ka.

4.2 Radiation patterns

The 3D measurement system is shown in Figure 6. The antenna under test (AUT) was aligned in the xy-plane, centred on a circular ground plane measuring 400 mm in diameter.

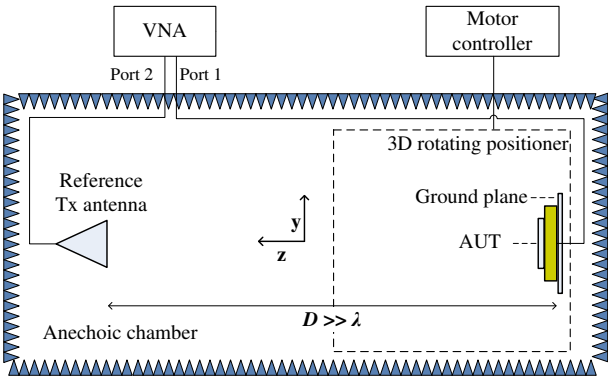


Fig. 6: Radiation pattern measurement setup in anechoic chamber.

3D radiation patterns were recorded for two orthogonal polarisations E_θ and E_ϕ, with positioner resolutions of $\Delta\theta = 1^\circ$

and $\Delta\phi = 10°$. For brevity, only total power E_{total} patterns can be given here. The power patterns measured at the resonant frequencies of the hexaferrite and RT5880 antennas are compared to the simulated patterns in Figures 7 and 8. The patterns were consistent with the TM_{10} mode, with the pattern similarity across the frequency range indicating that the radiating mode did not change. The increase in directivity with frequency was an artefact of the increasing electrical size of the fixed ground plane with respect to the decreasing operating wavelength, reducing diffraction into the $-z$ hemisphere.

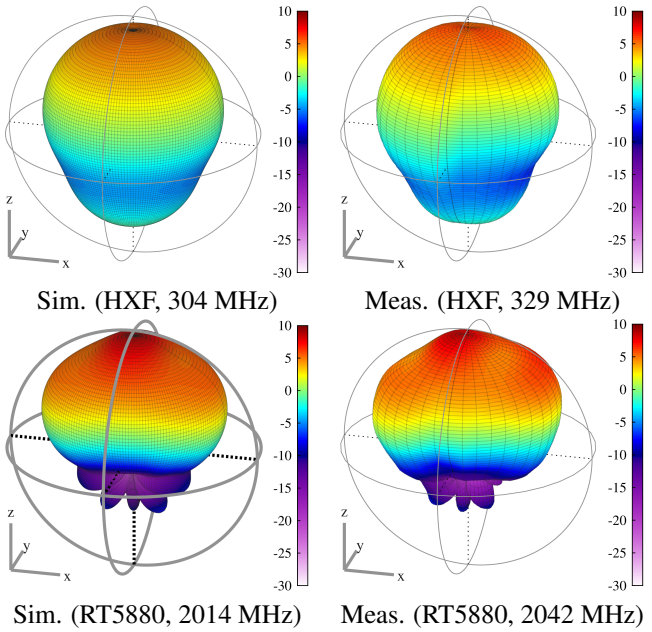


Fig. 7: E_{total} directivity patterns for large patch antenna.

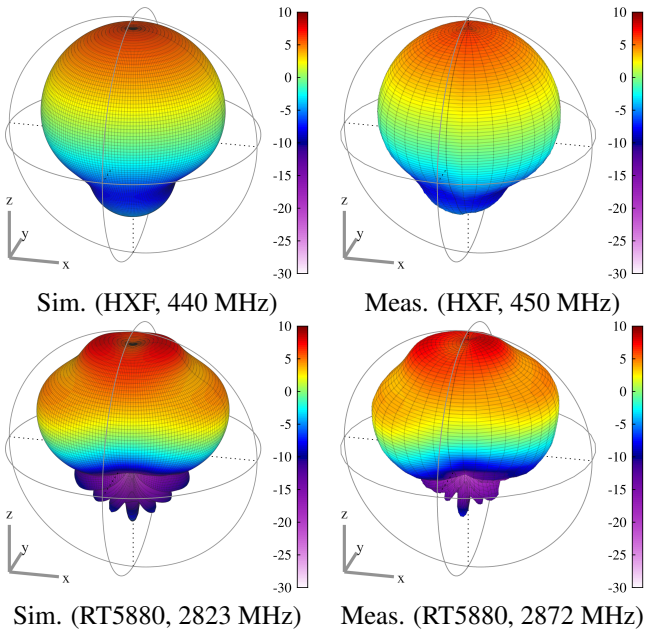


Fig. 8: E_{total} directivity patterns for small patch antenna.

4.3 Radiation efficiency

The radiation efficiency was calculated via a pattern integration method [14]. The total efficiency $\eta = \eta_m \eta_\Omega$ is given by rearrangement of gain $G = (\eta_m \eta_\Omega) D$, with directivity D and matching efficiency η_m. Radiation efficiency η_Ω consists of losses in the conductor, the substrate and the radiation resistance r_{rad}:

$$\eta_{\Omega,\mathrm{AUT}} = \frac{r_{\mathrm{rad}}}{r_{\mathrm{rad}} + r_{\mathrm{loss}}} \tag{2}$$

The pattern-integrated received power of the AUT was measured relative to that of a wire $\lambda/4$ monopole constructed for each frequency to determine total efficiency $\eta_m \eta_\Omega$. The ratio of overall efficiencies $\eta_{\mathrm{AUT}}/\eta_{\mathrm{ref}}$ permits efficiency calculation since the quarter-wave metallic monopole is recognised to be highly efficient [14], thus for comparison purposes it can be assigned a radiation efficiency value of $\eta_{\Omega,\mathrm{ref}} = 1$. Scaling the measured overall efficiency ratio by the matching efficiencies yields a measure of the radiation efficiency for the AUT at each frequency:

$$\frac{\eta_{\Omega,\mathrm{AUT}}}{(\eta_{\Omega,\mathrm{ref}} = 1)} = \frac{\eta_{\mathrm{AUT}}}{\eta_{\mathrm{ref}}} \times \frac{\eta_{\mathrm{m,\,ref}}}{\eta_{\mathrm{m,\,AUT}}} \tag{3}$$

The radiation efficiencies given by Eqn. 3 are given in Figure 9 for each of the antennas.

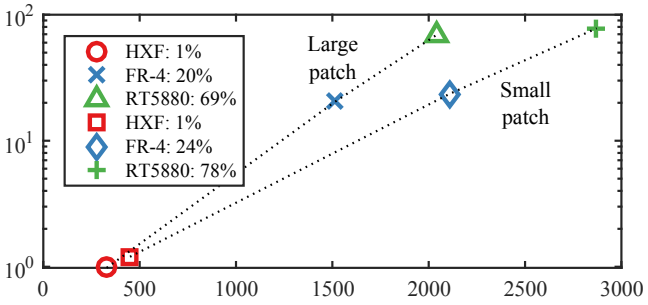


Fig. 9: Radiation efficiency relative to reference $\lambda/4$ wire monopole of low loss.

The RT5880 substrates delivered greater radiation efficiency than the FR-4 substrate, which was in turn much more efficient than the hexaferrite substrate. This can be understood as a combined effect of increased loss tangent of hexaferrite and FR-4 than that of RT5880 and falling r_{rad} as the electrical size of the antenna is reduced with respect to the free space wavelength (documented by the ka factor in Table 2).

Electrically small antennas with $ka < 0.5$ are recognised to be susceptible to low radiation resistance, reducing efficiency even for fixed values of substrate loss (Eqn. 2) [4]. While the hexaferrite antennas remained resonant in terms of substrate wavelength, they nevertheless had small physical apertures. The authors therefore contend that while the loss tangents of the hexaferrite materials in development might be considered

low with respect to other ferrites in the UHF band by material scientists [13], the loss tangents need to be reduced much more aggressively to cope with the reduced r_{rad} coincident with the enhanced miniaturisation offered by hexaferrite substrates.

5 Conclusions

A magneto-dielectric hexaferrite substrate was characterised across the frequency range 1–1000 MHz. At the tested antenna frequencies of 329 MHz and 450 MHz it was found to have a refractive index of $n = \sqrt{\mu_{\text{r}} \times \varepsilon_{\text{r}}} = 12.3/13.0$ and loss tangents of approximately $\tan\delta_{\varepsilon} = 0.18$ and $\tan\delta_{\mu} = 0.10 - 0.18$. The hexaferrite material exhibited a close wave impedance match to 377 Ω across the measured band. The high refractive index and reasonably high filling factor of the substrate compared to *e.g.* hexaferrite-chip loaded designs gave a frequency reduction factor greater than six relative to the same-sized antenna on Rogers RT5880 substrate.

The low measured efficiency of the hexaferrite antennas suggests that material loss tangent has a profound effect on the utility of hexaferrite materials, potentially precluding hexaferrite use for efficient miniaturisation of patch antennas for long range communication. On the balance of the challenges of efficiency versus miniaturisation, the authors are in agreement with the findings of [3] that hexaferrite patch antennas are best suited to miniaturisation-critical applications such as short range antennas for wearable or RFID applications, or compact receivers where the received signal strength is already low. Determination of target loss tangents for efficient performance with respect to rapidly reducing r_{rad} with increasing miniaturisation could represent an extension to the present work.

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